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Mechanical Concepts for Simulation of Nonlinear Engine Suspension on Aeroelastic Demonstrator

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Abstract: The paper is focused on the design and development of the system simulating nonlinear attachment of the engine on the aeroelastic demonstrator. The aim is at obtaining the nonlinear (i.e., amplitude dependent) modal characteristics of the engine pitch vibration mode. Three mechanical concepts were tested to simulate the incremental stiffness characteristic of the engine pitch attachment. The concepts are described and compared. The nonlinear demonstrator (NOLWING), which include nonlinear engine pitch as well as nonlinear aileron flapping mode is utilized for research and development of the advanced methods for the identification of nonlinear modal parameters and aeroelastic wind tunnel testing aimed to development and validation of the active control systems (gust alleviation, etc.).

Keywords: Aeroelastic Experiment; Magnetic Spring Concept; Ball Rubber Spring Concept; Flat Rubber Spring with Plug Concept.

1 Introduction

This article is focused on the design and development of the system simulating nonlinear attachment of the engine on the aeroelastic wing / engine component demonstrator. The intention for the nonlinear aeroelastic demonstrator development arose in connection with a project focused on the research of new methods for ground vibration testing including nonlinearities (see [1–5]). Modal characteristics of aircraft structures are always more or less nonlinear (i.e., dependent on the vibration amplitude). Nonlinear effects are caused mainly by the structure geometry or by the friction or backlash. The modal testing using phase resonance method allows to characterize these nonlinearities. Nonlinear effect is characterized as dependence of the particular parameter (e.g., natural frequency) on the vibration amplitude [6–9].

Provided the nonlinear effect is small, the structure response to the harmonic excitation is quasiharmonic and can be expressed by the equation including amplitude dependent damping and stiffness term. Nonlinear stiffness causes the asymmetric resonance peak, whereas nonlinear damping influences amplitude-phase curve.

A typical nonlinear behavior of riveted aircraft structure is decreasing of a natural frequency and approaching the asymptotic value with increase of the amplitude. This is caused by the contact surfaces of rivets (or bolts) and the structure. Provided the external forces are lower than the friction forces, the contact surfaces are mutually fixed. Increasing the external forces, the contact surfaces become to slide. This sliding effect is limited by the backlash in the rivet or bolt joints. Then the deformations become elastic again. Sliding effect decrease the modal stiffness which causes decreasing of the natural frequency. The same effect is also valid for the damping. The described nonlinear effect is small and the structure response can be expressed by the linear model. Nevertheless, even small nonlinear effect may cause troubles in the process of the modal testing. The accuracy of the test results is dependent on the method for identification of particular modal parameters, selected by a test engineer [10]. Despite there are standard procedures and recommendations available, the final approach is selected according the engineer's experience [11].

Much more complicated problems may be caused by the large nonlinearities caused by dry friction or backlash inside bearings or pin joints, e.g., in the control surfaces actuation systems [12], etc. The natural frequency may vary significantly (by 10 - 20%) and the structure response must be described by fully nonlinear equation. The modal parameters have large variance and may be time varying [13]. This is a typical behavior of the control surface flapping modes. The identification of modal parameters is very complicated and the specific methods for the nonlinear parameters identification must be employed. The research of such appropriate processes and methods is necessary.

The nonlinear aeroelastic demonstrator ”NOLWING” was developed as a research test bed for the research of advanced experimental methods for identification of nonlinear modal parameters. Another utilization of the demonstrator is research and experimental validation (wind tunnel testing) of the systems of active control aimed to suppress the structural vibrations, e.g. for a gust alleviation. The demonstrator was adapted from the former aeroelastic model of the L-610 Czech twin turboprop commuter for 40 passengers.

2 Demonstrator Description

The aeroelastic model has a length scale of 1/5 and a velocity scale of 1/6. The complete aircraft model was tested in TsAGI Zhukovskij in a 7 m diameter wind tunnel. Wing / engine and tailplane / fin component models were tested in VZLU 3 mm diameter wind tunnel. The starboard wing / engine component model with a span of 2.56 m was utilized for the ”NOLWING” demonstrator [2]. The main dimensions of the wing are shown in Fig. 1.

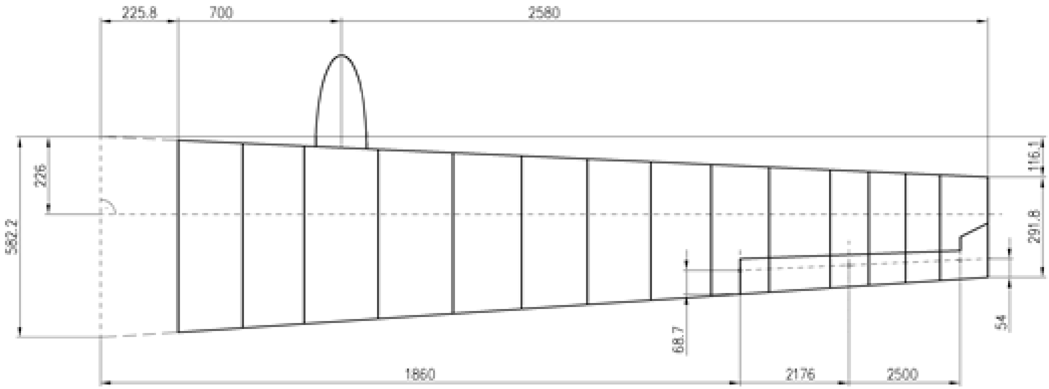

Fig. 1: NOLWING Aeroelastic Demonstrator - System Drawing.

The main demonstrator scale factors are summarized in Tab. 1.

The wing stiffness was modeled via duralumin spar with the H-cross-section. The aileron stiffness was modeled by the duralumin spar with the rectangular cross-section. The wing was divided into 14 sections spanwise with the lead weights modeling the wing inertia; the aileron was divided into 6 sections spanwise. The aerodynamic shape of the wing was realized by means of a balsa and paper structure. Aileron and spoilers were controlled by means of hydraulic mini-cylinders. Aileron actuation stiffness was made variable by the use of replaceable spiral steel springs (see Fig. 2).

The engine was connected through cross-spring pivots modeling the engine bed stiffness (pitch and yaw). Engine mount-isolators were modeled via metal strip springs. All these springs were replaceable as well. For the detailed description of the engine connection model see Fig. 3. As an option, the nonlinear spring aimed at obtaining the nonlinear characteristics of the engine pitching mode and the nonlinear aileron actuation stiffness [17] aimed to get the nonlinear characteristics of the aileron flapping mode are applicable. The aggregate picture of the demonstrator is in Fig. 4.

3 Magnetic Spring Concept

The first tested concept of the nonlinear engine suspension was the magnetic spring [18]. It was developed on the principle of a vibration micro-generator for the passive systems installed on the vibrating structure. The concept was adjusted according to the character of the expected excitation (see Fig. 5).

Side magnets were attached to the engine bed. The central magnet and the engine mass were attached to the rigid arm which was connected to the engine bed by a pivot. Springs (k) represent the linear centring spring which is an ordinary attachment of the engine (crossspring pivot); the spring constant is changeable within

Tab. 1: NOLWING Aeroelastic Demonstrator - Main Scales.

Quantity	Scale
Length	0.200
Velocity	0.166
Structure density	2.128
Mass	0.017
Frequency	0.833
Bending and torsional stiffness	9.460e-5

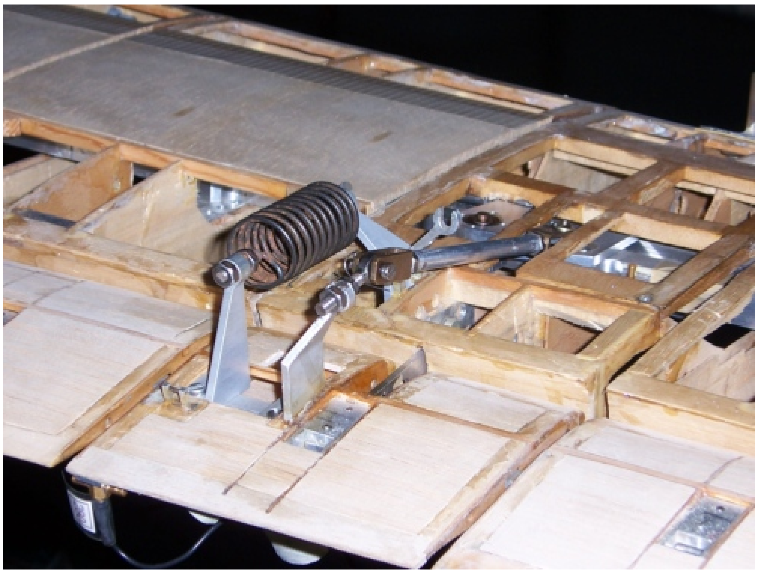

Fig. 2: Aileron Actuation and Aileron Stiffness Simulation.

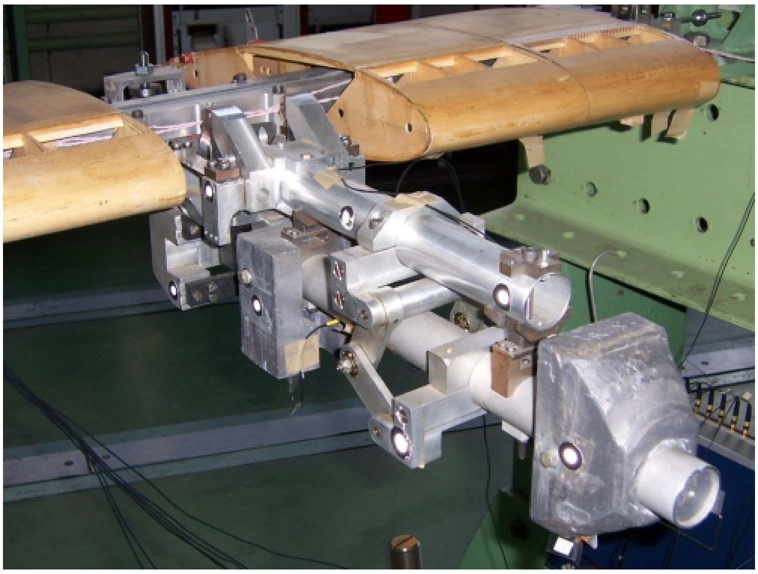

Fig. 3: Engine Suspension Model (1 - Yaw Cross Spring; 2 - Pitch Cross Spring; 3 - Front Mountisolator Spring; 4 - Non-linear Spring; 5 - Engine Mass).

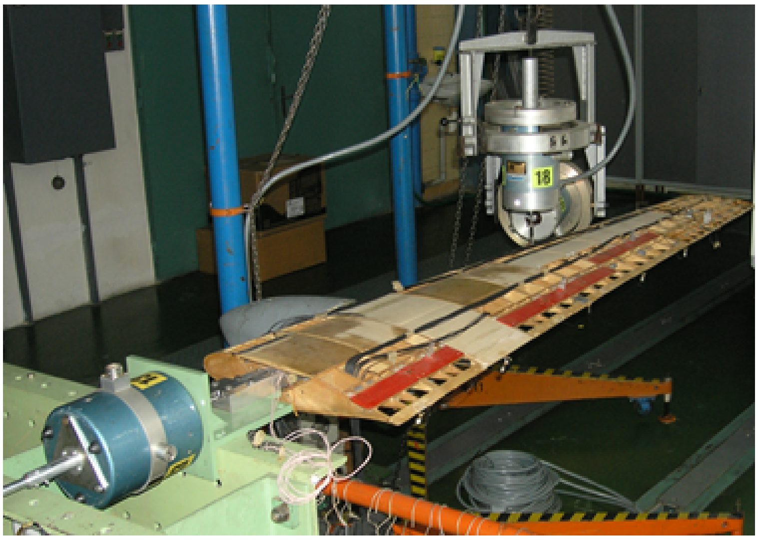

Fig. 4: NOLWING Aeroelastic Demonstrator.

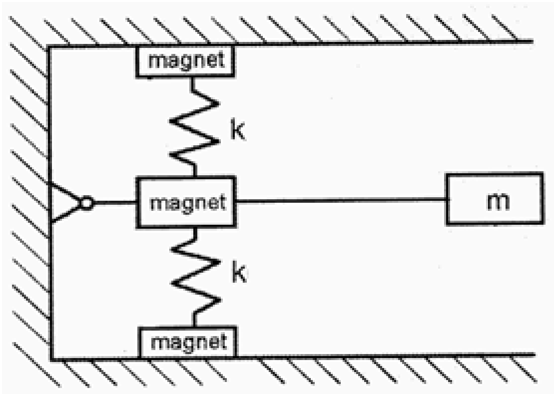

Fig. 5: Magnetic spring concept.

the range of ± 30 % via the replacement of steel spring leaves. Three types of ring-shaped magnets were used considering the dimensions and forces: Neodymium N32N42 D29/d9.2 × 8 Ni (spring A), neodymium N16N35H D11.7/d5.2 × 8 Ni (spring B), ferrite F32Y35H D28/d6.5 × 10.

The characteristics of magnetic springs were obtained by static measurements. Fig. 6 demonstrates the arrangement of the test. Fig. 7 shows the magnetic repulsive force as a function of the central magnet position, the parameter is the distance of both side magnets, and the corresponding spring stiffness curves are given in Fig. 8.

The dynamic stiffness was tested on the cantilevered engine and the engine bed system (Fig. 9). Excitation force was applied in the vertical and lateral direction respectively. The engine pitching frequency was evaluated as a function of the central magnet deflection; the parameter was the distance of side magnets.

The magnetic spring increased the engine pitching frequency by about 1.0 Hz, but the decreasing of frequency with increasing amplitude is barely noticeable in the figure. The total stiffness is the superposition of linear and nonlinear stiffness components, the former being the decisive one. Hence, the magnetic spring concept has not been applied to the demonstrator as the final solution. On the other hand, the advantage is that the magnetic spring works fluently with no mechanical shocks. The exploitation of the magnetic spring concept would require further development and adjustments of the design solution. This will be the subject of our future work.

4 Ball Rubber Spring Concept

Another concept of the nonlinear engine suspension, the ball rubber spring concept [19] is based on two rubber half-balls with a central steel contact plate (Fig. 10). Two types of rubber balls were used: minigolf ball

Fig. 6: Magnetic spring static test arrangement.

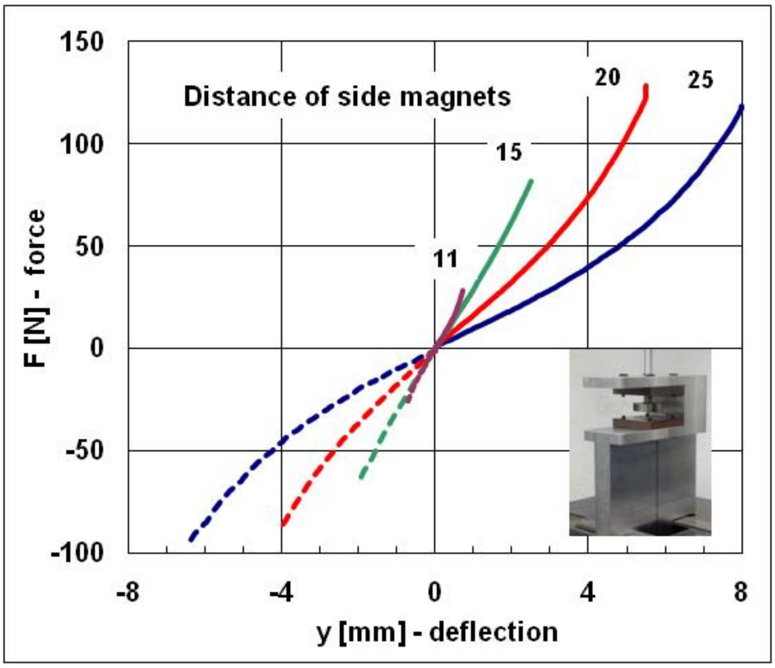

Fig. 7: Static repulsive force - spring A.

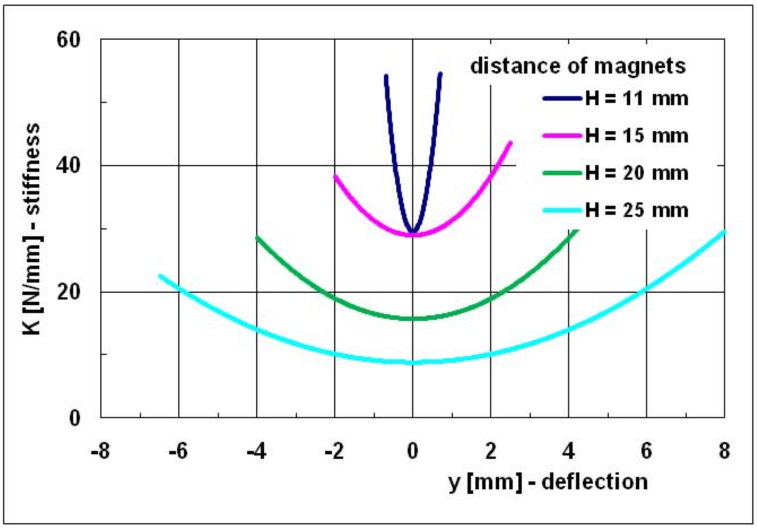

Fig. 8: Static deformation curve - spring A.

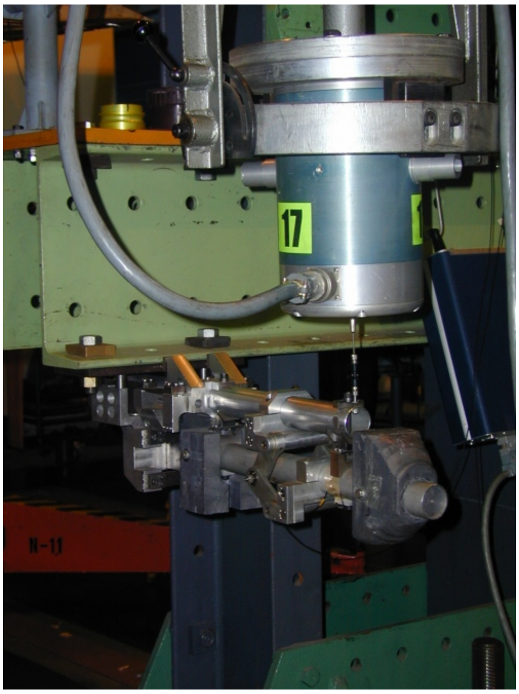

Fig. 9: Magnetic spring dynamic test arrangement.

- middle hardness (spring A) and children's playing ball (spring B).

The deformation curves of balls were calculated by means of the finite element analysis (Fig. 11), and the results were compared to the static stiffness tests (Fig. 12). The aim of the analysis was to make an estimation of the Young's modulus and Poisson's ratio of the rubber. Also the impact of boundary conditions applied to the half-ball baseline was checked.

The dynamic stiffness was measured using a simple fixture (Fig. 13). The system was excited by means of an electromagnetic shaker. Harmonic excitation signals with constant amplitude (0.25 - 1.75 mm) and specific frequencies (1.0 - 5.0 Hz) were used. The force amplitude was measured as a function of the excitation amplitude, and the parameter was the initial stretch of ball-springs.

The influence of non-linear spring effect on the engine pitching mode was evaluated by means of a similar test arrangement as for the previous concept (cantilevered engine and engine bed). Initial stretch, excitation amplitude and frequency sweep direction were evaluated as the parameters. The ball spring constant (K) is demonstrated as a function of excitation amplitude (y), initial stretch (y0) and excitation frequency (f) in Fig. 14 and Fig. 15. The frequency peaks of the amplitude-frequency characteristics of engine pitching mode are shown in Fig. 16.

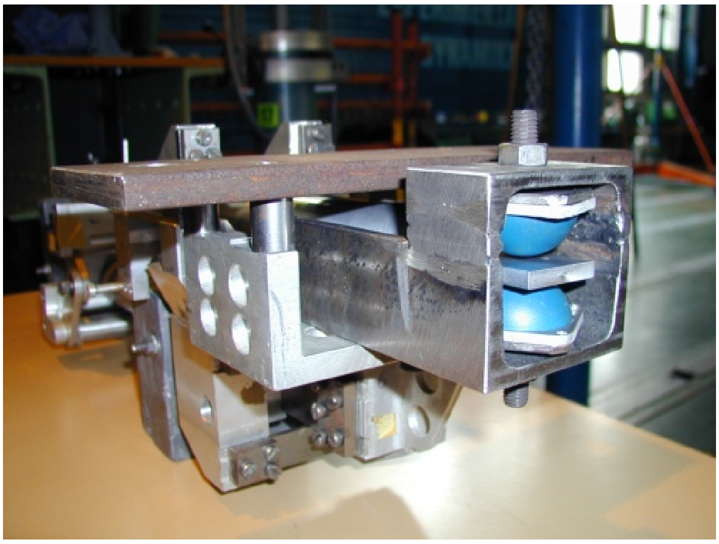

Fig. 10: Ball rubber spring concept.

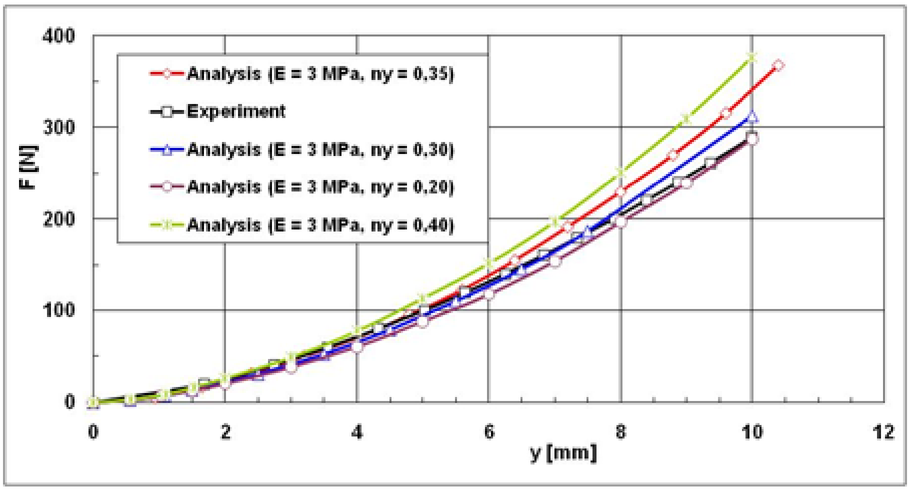

Fig. 11: Ball rubber spring deformation curves.

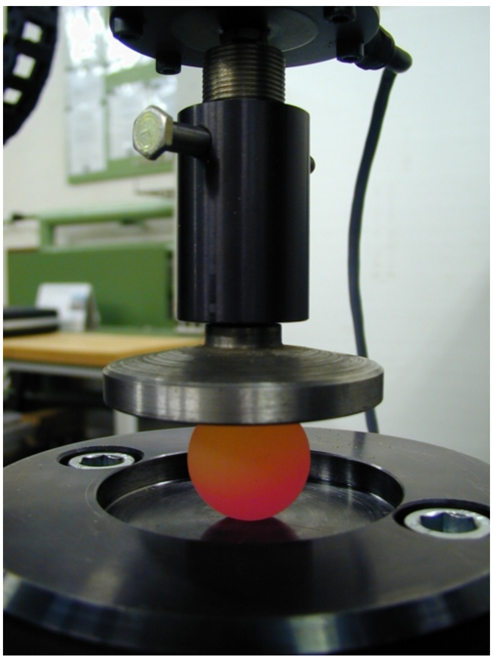

Fig. 12: Ball rubber spring static stiffness test arrangement.

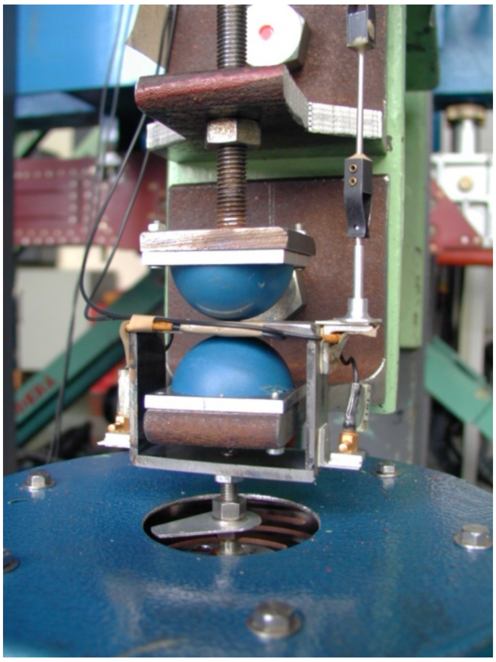

Fig. 13: Ball rubber spring vibration test.

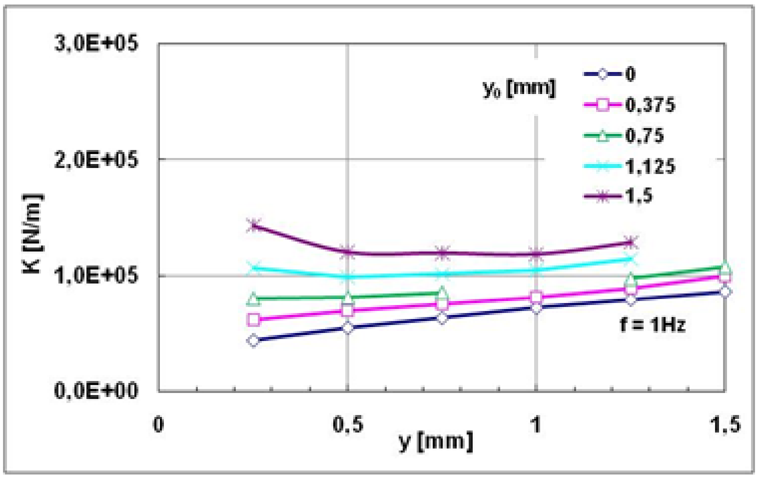

Fig. 14: Stiffness constant vs. shift amplitude (ball spring type A).

The ball rubber spring was applied in parallel with the ordinary linear cross-spring pivot which also defines the engine pitching mode pivot point. The characteristics of the nonlinear ball spring are influenced by the material used; the initial stretch makes the spring constant increase. The disadvantage of the concept is additional friction among half-balls and central plate due to lateral engine vibrations.

5 Flat Rubber Spring with Plug Concept

The last concept of the nonlinear engine suspension is the flat rubber spring with plug [20] concept. It is similar to the previous one. There are spherical or cone shaped steel plugs instead of the rubber balls and a flat sandwich contact plate instead of the steel one. The contact plate consists of the two rubber side layers attached to the steel core layer on both sides.

Several different rubber materials (MATADOR 04, MATADOR 869, MATADOR 818, RUBENA 8708) and several plug types with the spherical / cone shape were used - see Fig. 17.

The rubber material characteristics were given by static tests. There is an example of measured deformation curves with approximation used for analyses in Fig. 18.

The deformation curves of different plug shapes and rubber materials were calculated by means of finite

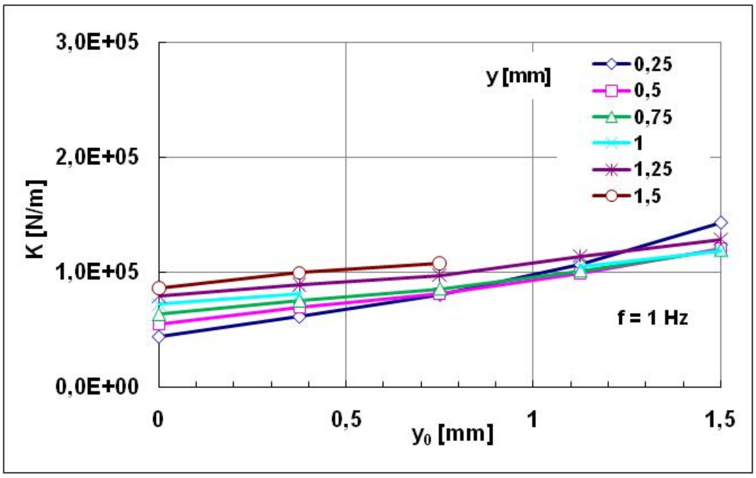

Fig. 15: Stiffness constant vs. initial stretch (ball spring type A).

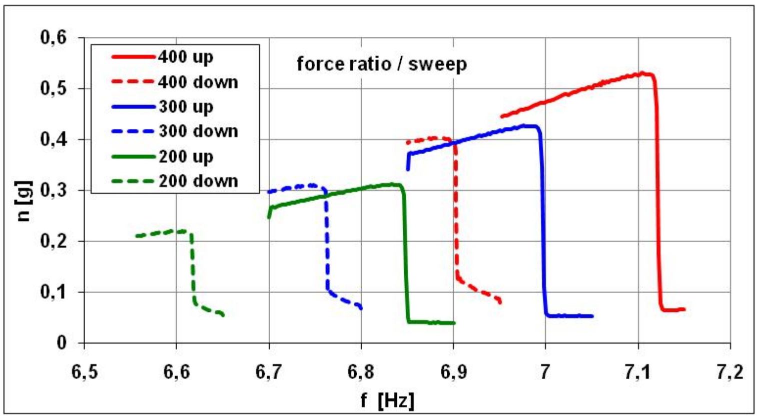

Fig. 16: Amplitude-frequency characteristics vs. actuating frequency (ball spring type A).

Fig. 17: Plug (example) - Ball R = 10 mm, cone 70°.

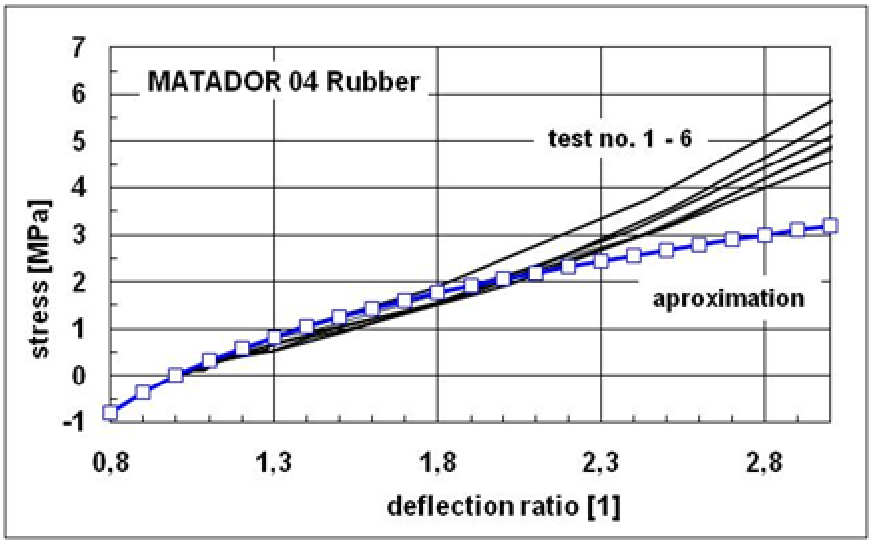

Fig. 18: Deformation curves - MATADOR 04 rubber.

element analysis. The comparison of curves is presented in Fig. 19. It allows evaluating the influence of plug shape, rubber material and a boundary condition. Selected configurations of the plug shape and rubber material were then validated by means of the tests (see Fig. 20).

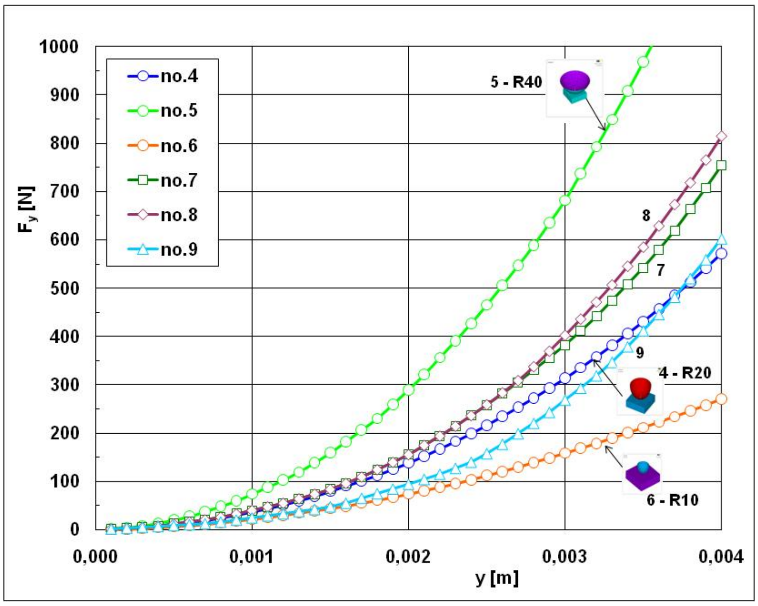

Fig. 19: Flat rubber spring with plug concept - comparison of analytical deformation curves.

The dynamic measurement of flat rubber spring with plug concept was realized on the complete half-wing / engine aeroelastic model. The configuration of MATADOR 04 rubber and a plug with the sphere - cone shape (sphere radius of 20 mm, cone angle of 72 deg) was tested. The parameter was the amplitude of the harmonic excitation force. As in previous concepts the flat rubber spring is applied in parallel with the linear cross-spring pivot. The next few figures show the transfer functions of the signal from accelerometer placed at the excitation point. Fig. 21 shows the measurement of the nominal linear attachment (cross spring pivot). The minimal shift of natural frequency increasing the excitation force amplitude demonstrates the linear character of the engine attachment. Fig. 22 shows transfer functions of the measurement of parallel cross-spring pivot and flat rubber spring attachment. The natural frequency increased significantly and at the same time, became dependent on the excitation force amplitude. It demonstrates the nonlinear engine attachment. The rubber plate was lubricated at the contact point in order to minimize the friction of horizontal engine vibration.

Contrary to previous concept, the flat rubber spring with plug allows a wider possibility of tailoring the nonlinear deformation characteristic by varying the configurations of plug shape and rubber material. This

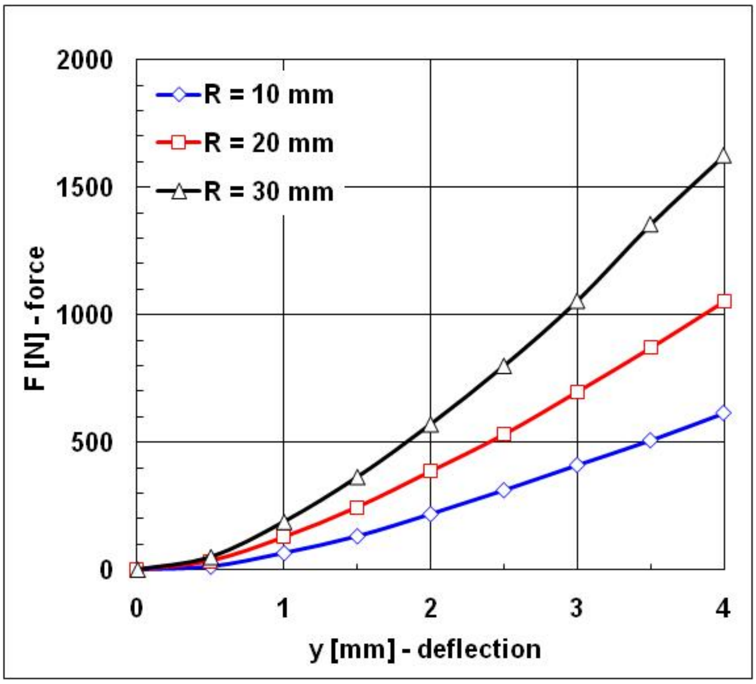

Fig. 20: Flat rubber spring with plug concept - measured deformation curves - influence of plug shape.

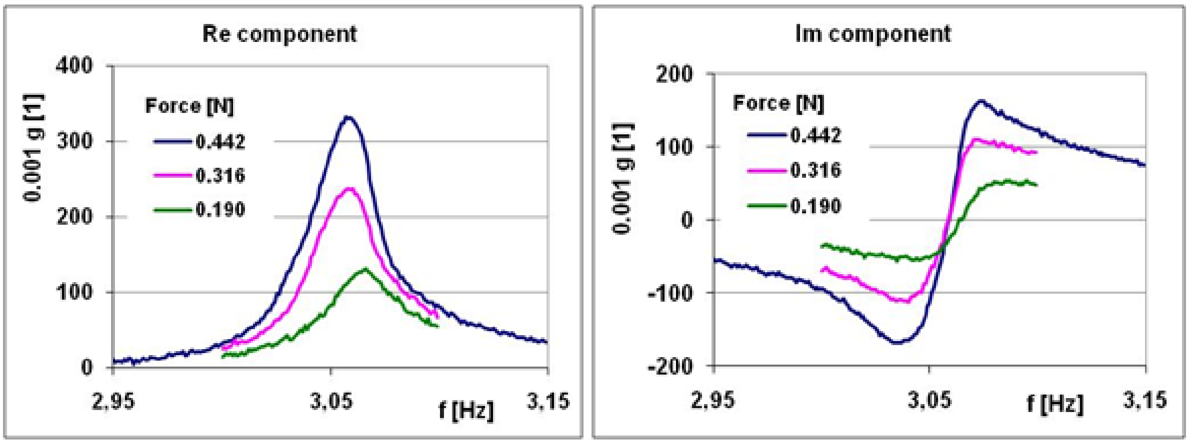

Fig. 21: Engine vertical vibrations - linear attachment (cross spring pivot).

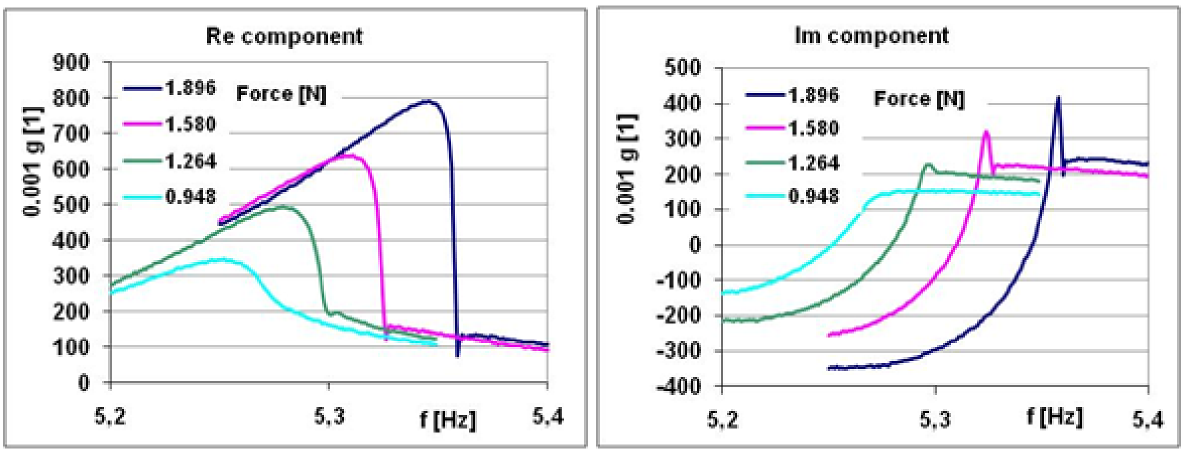

Fig. 22: Engine vertical vibrations - nonlinear attachment (cross spring pivot and flat rubber spring).

concept was finally chosen to be used on the NOLWING demonstrator. Currently there are four prepared configurations for rubber materials and three plug shapes which give us twelve different types of nonlinear characteristics. Moreover, it is also possible to vary the ordinary linear attachment stiffness (by ± 30%) via replacing of cross-spring pivot leaves.

6 Comparison of Concepts

Fig. 23 summarizes the measured spring constants of the different concepts. It includes the nominal linear cross-spring pivot stiffness, the magnetic concept springs and the ball rubber concept springs. The magnetic spring concept advantage is fluent work with no mechanical shock, however the effect of non-linearity is too low. The ball rubber spring concept effect of nonlinearity is noticeably higher. On the other side, the problem of this concept is the friction caused by the lateral movement of components. The flat rubber spring with plug concept has similar characteristics as the previous one, however it is much easier to adjust the spring non-linear characteristics by means of the change of the plug shape. The variability of the flat rubber with plug concept (as demonstrated in Fig. 19) was the main reason, why this one was finally applied to the demonstrator.

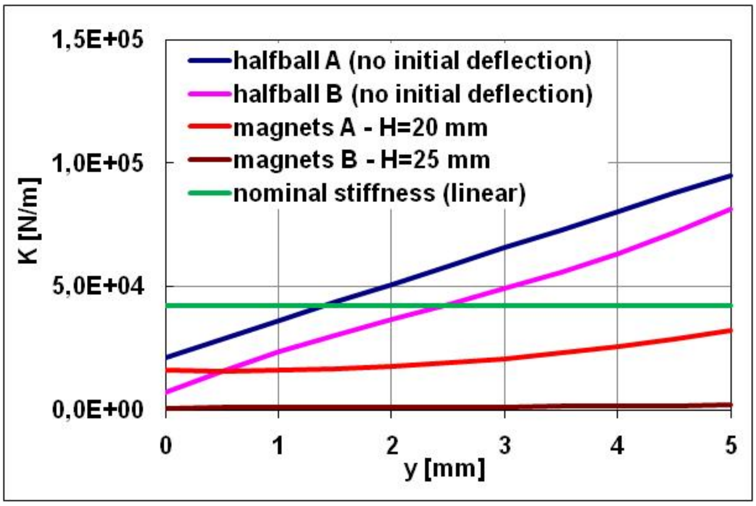

Fig. 23: Spring constants - comparison of concepts.

7 Conclusion

This article is focused on the design and development of the system simulating nonlinear attachment of the engine on the aeroelastic wing / engine component demonstrator. The demonstrator is intended for researching experimental methods of ground vibration testing including nonlinearities and validation of analytical methods and models. Another utilization include aeroelastic wind tunnel tests aimed for research and validation of systems for the active control of vibrations, e.g. for gust alleviation. The demonstrator was adapted from the former aeroelastic model of the Czech commuter for 40 passengers. Three concepts of nonlinear attachment of the engine were tested. The Flat Rubber Spring with Plug concept was finally chosen to be used on the demonstrator.

Apart from the nonlinear attachment of the engine, the demonstrator includes also nonlinear attachment of the aileron actuation simulating nonlinear characteristics of aileron flapping mode using Active Electromagnetic Spring concept [17]; therefore, the demonstrator represent complex linear or nonlinear wing / engine component demonstrator of the commuter aircraft structure.

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